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Improvements to Vertical Axis Wind Turbine Blades to Aid in Self-Starting

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Improvements to Vertical Axis Wind Turbine Blades to Aid in Self-Starting

(TITLE)

BY

Joseph P. Tillman

THESIS

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THESIS

Improvements to Vertical Axis Wind Turbine Blades to Aid in Self-Starting

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Starting Improvements for H-Rotor Vertical Axis Wind Turbines

Joseph P. Tillman

(Abstract)

This study investigated improvements in airfoil or blade design to aid in the starting of an H-rotor type vertical axis wind turbine (VAWT) and how these changes would affect the performance of an H-rotor VAWT. Based upon previous research and aerodynamic models, the hypothesis that using asymmetric airfoils designed for lower Reynolds' numbers would be effective in generating enough lift to overcome the starting inertia and that the H-rotor VAWT would self-start.

This hypothesis was first tested on small homemade wind turbines to determine if asymmetric airfoils would self start the VAWT. Later, various small airfoils were tested on the same small generator to find the better performing airfoil. Afterwards two larger homemade wind turbines were built. The first turbine constructed was a small, three rotor horizontal axis wind turbine (HAWT) with a swept area of approximately 1.5 m^2. This turbine used small yet high performance plastic filled airfoils. The second wind turbine was a VAWT with three rotors rotating in an equal swept area of approximately 1.5 m^2 yet utilizing homemade asymmetric airfoils.

Both these 1.5 m^2 homemade turbines utilized the same make and model of direct current treadmill motor in the use of DC generator. Both turbines used identical voltage recording and data logging devices which measured and logged the voltage output across a known resistance in various wind speeds. Wind speed was measured using a data logging anemometer.

The results of the field tests indicate that asymmetric airfoils are effective in allowing H-rotor VAWTs to self-start though efficiency comparisons could not be accomplished.

To

Catherine J. Tillman

Beloved wife

&

Mary P. Tillman

Beloved mother

Acknowledgements

This research owes its existence to the support, patience, and guidance of the several individuals. First, I would like to thank the members of my research committee: Dr. Samuel Guccione, Dr. Rigoberto Chinchilla, and Dr. Peter Ping Liu. Dr. Guccione was gracious in his providing both material and direction for the research. Dr. Chinchilla was a great editor and provided great assistance in getting parts of this thesis published. Dr. Liu served both in aiding my decision to attend Eastern Illinois University as well as overseeing my research.

Secondly, I would like to thank Durward Askew, Steven McDevitt, Marc Seigfried, (Uncle) Cletus Graden, and Dennis and Robin Hostetter for their time, workshops, skills and assistance in constructing the various turbines used in this research. Without their contributions, this research would not have been possible. I would also like to thank Nathan Smith and Ray Amerson, Jr. for their creation of several of the diagrams used in this thesis. Nathan Smith also deserves special mention as a capable engineering assistant who helped me during blade design and final testing.

Finally, the author wishes to thank my family, especially my mother, Mrs. Mary Tillman, and my wife, Mrs. Catherine Tillman, for their undying support and patience throughout this degree and research. A special note of gratitude to my late father, Jim Tillman, believed in the importance of a good education and an honest day's work.

Table of Contents

List of Tables

List of Figures

CHAPTER 1

Introduction

At the beginning of the 21^{st} century, nations are realizing that the fossil fuel supply will not last indefinitely and that emissions from the combustion of coal and petroleum pose possible dangers to the environment. Cleaner and more abundant alternative energy sources are needed. One such energy source is wind.

Wind turbine design currently focuses on horizontal axis wind turbines (HAWTs) where the blades or airfoils sit on top of a tower and rotate parallel to the direction of the wind. Vertical axis wind turbines (VAWTs) comprise an older but lesser known family of wind machines. A type of VAWT, the straight bladed vertical axis wind turbine (SBVAWT), offers several potential advantages over the standard horizontal axis wind turbines which are now in common use worldwide.

Historically, SBVAWTs have lacked the ability to reliably self-start in low wind conditions. Various methods have been tried to overcome this problem including adding electric starting motors (Islam, Ting, and Fartaj, 2007), incorporating a relatively inexpensive variable pitch device for the blades (e.g., Cooper and Kennedy, 2005; Tristanto, 2005), and adding small Savonius rotors to the central shaft (Biswas, Gupta, and Sharma, 2008). Unfortunately, these methods have added expense and maintenance to the turbine and, in some cases, decreased performance.

By exploring past and current airfoil research, two airfoil design are developed and tested that allow SBVAWTs to self start in low wind speeds of less than 4.0 m/s or approximately 9 mph. Incorporating these improvements in a SBVAWT may allow a VAWT design to finally see greater use in the small to medium size wind markets and make significant contributions in the distributed power generation arena.

Statement of Research

As a result of this study, a method will be develop an airfoil or blade design which will enable a SBVAWT to self start under low wind conditions of less than 4 m/s or approximately 9 mph.

Hypothesis

It is believed that an airfoil or blade can be developed to allow a SBVAWT to self start in low wind condition of 4.0 m/s.

Definition of Terms and Nomenclature

A	Area swept by turbine
c	Blade cord
C_p	Power coefficient (a measure of turbine efficiency)
D	Diameter of the turbine
dBA	Sound pressure level
HAWT	Horizontal axis wind turbine
H	Height of turbine
KE	Kinetic energy
Laminar flow	streamline or non-turbulent flow of air

mph	miles per hour
m/s	meters per second
N	Number of blades
NACA	National Advisory Committee for Aeronautics
P_o	Overall power
P_n	Net power
R	Radius of turbine
RN	Reynolds number
rpm	revolutions per minute
SBVAWT	Straight bladed vertical axis wind turbine
TSR	Tip speed ratio ($R\omega / V_\infty$)
Turbulent air	Air flow characterized by chaotic property changes
VAWT	Vertical axis wind turbine
V	Linear air velocity
$V_{\text{cut in}}$	Cut in speed or the speed at which a turbine begins to rotate with one complete revolution
θ	azimuth angle
η	Efficiency due to friction, gearbox, and electrical losses
σ	Solidity (N_c/R)
ω	angular velocity of the turbine in rad/sec

Assumptions

The following assumptions are made regarding this research:

1. During testing, the linear wind velocity, V, is approximately steady at a given turbine location.
2. Airflow will be equally non-turbulent around airfoils of sanded wood and extruded styrofoam.
3. All tested SBVAWTs will approximately encounter the same shaft, bearing, and armature resistance.
4. The horizontal distance from the shaft affects all SBVAWTs equally despite differing cord lengths that may exist.

Limitations

The following limitations are made regarding this research:

1. Wind speed data is dependent upon the anemometers' precision and accuracy.
2. Manufacturing accuracy and tolerances are based upon hand tools and simple power tools.
3. Data collection is based upon the voltage and data logging resolutions and calibrations of the digital voltmeters and digital anemometers.

Delimitations

The following delimitations are made regarding this research:

1. This research is limited to airfoils of asymmetric cross section.
2. The blade materials for the SBVAWT is limited to wood, extruded Styrofoam, and plastic covering.
3. This research is focused on airfoil applications for SBVAWTs.

CHAPTER 2

Wind Technology

2.1 Overview of Modern Wind Energy

Wind energy is a form of solar energy. It is estimated that approximately 3% of the Sun's thermal energy is transformed into wind energy. Recent studies show that current wind technology operating in Class 3 (6.4 - 7.0 m/s) wind locations is capable of producing approximately 72 terawatts of electricity (Stanford Report, 2005). This is forty times the amount of electrical power annually consumed worldwide and this clean power source is just beginning to be tapped on a large scale.

Today, wind energy is rapidly developing into a significant component of electrical generation. Over 159,000 megawatts of wind generation were operational world wide by the end of 2009 with 38,312 megawatts added in 2009 alone (World Wind Energy Association, 2010). The United States currently has the largest wind powered electrical generating capacity of any nation, 35,000 megawatts (MW), and its domestic wind energy industry had enjoyed a five year growth rate of 39% (AWEA, 2010). The reasons for this growth are straightforward.

Wind is a vast energy resource which is clean and renewable. It can be utilized by both developed as well as developing countries. Improvements in power electronics, materials, and wind turbine designs allow manufacturing to continually lower the cost of wind generated electricity making it today economically viable compared with most other fossil fuels. For example, in early 1980, the cost of 1 kilowatt-hour (kWh) generated by wind was around $0.25. Today, this number is closer to $0.05 per kWh (da Rosa, 2009).

In the remainder of this thesis, the following terms will be used. A *wind machine* is any device that uses a breeze or the motion of the air to produce a force. A *windmill* refers to that type of wind machine that is used for mechanical actions such as grinding grain or pumping water. A *wind turbine* is a wind machine that is used to turn an alternator or generator in order to produce electricity.

2.2 Wind Resources

Usable wind speeds are measured on a scale divided into seven classes. These divisions are used to describe a range of wind speed as well as to give a numerical value for the amount of power per square meter, the *wind power density*. Table 1.1 shows the seven wind classes and the wind power density at 30 m or 98 ft.

Wind Class	**Wind Speed m/s (mph)**	**Power Density W/m^2**
Class 1	0-5.1 (0-11.4)	0-160
Class 2	5.1-5.9 (11.4-13.2)	160-240
Class 3	5.9-6.5 (13.2-14.6)	240-320
Class 4	6.5-7.0 (14.6-15.7)	320-400
Class 5	7.0-7.4 (15.7-16.6)	400-480
Class 6	7.4-8.2 (16.6-18.3)	480-640
Class 7	8.2-11.0 (18.3-24.7)	640-1600

Table 1.1: Wind Classes at 30 m. *(Courtesy of the National Renewable Energy Lab)*

Usually, one year's worth of data is required before a potential wind resource can be analyzed with any degree of accuracy. Anemometry data is usually taken at 30 m, 40 m, and 50 m along with temperature readings. As a general rule, wind speed is proportional to height. Higher wind speeds are encountered at increasing heights. For this reason, wind machines are mounted as high as possible. Many commercial turbines are now mounted at 80 m.

Typically, a site needs to demonstrate at least Class 3 winds before any commercial turbine is installed. Most of the smaller, household size turbines are also designed for Class 3 or better wind speeds. Though several locations throughout the United States enjoy favorable, Class 3 winds, several locations lack these winds. Many locations throughout the United States have Class 2 winds speeds or less. Figure 1 shows a map of the United States and the average annual wind speeds measured at 50 m. Areas of Class 1 and Class 2 winds appear as white in this diagram.

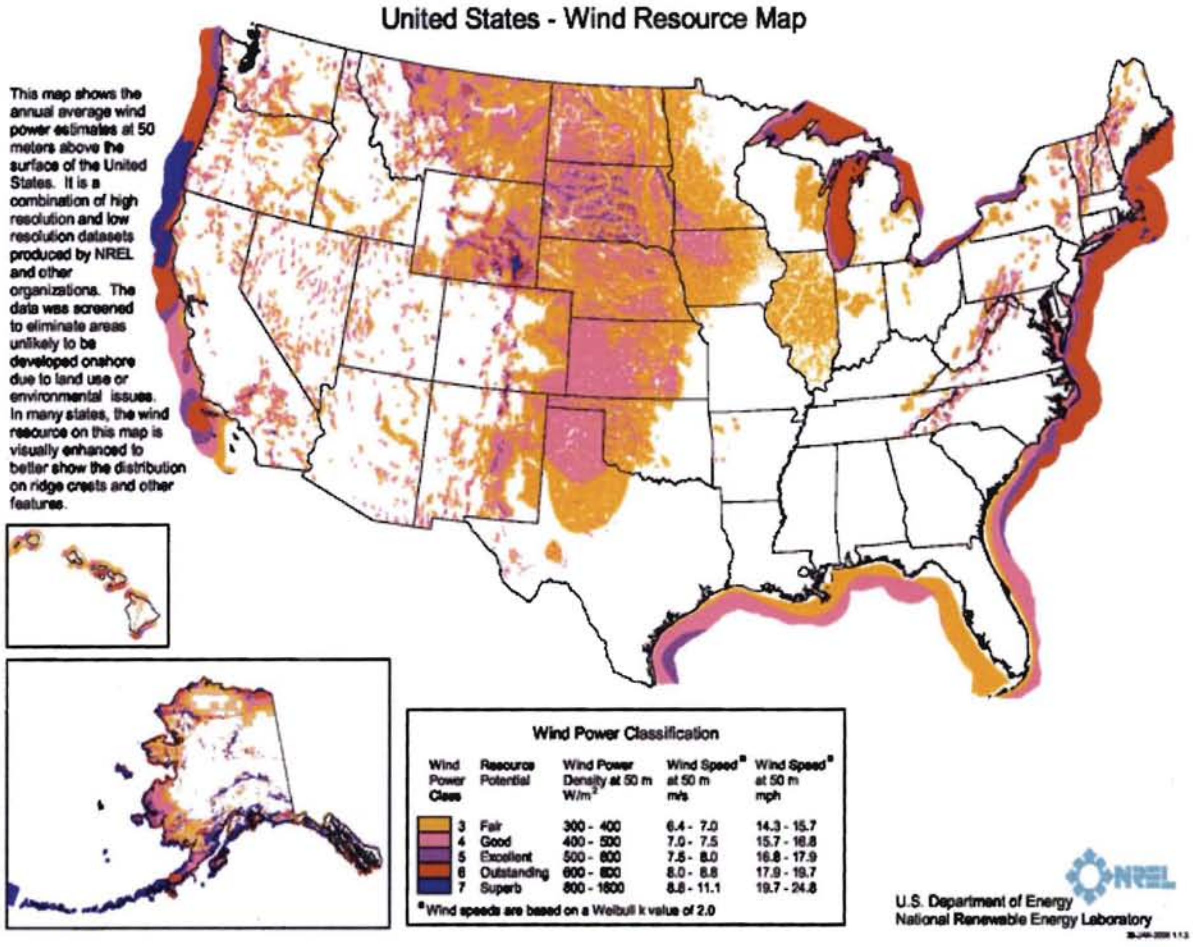

Figure 1: The 50 m wind speed map of the United States. *(Courtesy of the National Renewable Energy Lab)*

Summer months at temperate latitudes are often accompanied by Class 1 winds (Gipe, 2004). Class 1 wind speeds also predominate in the southern parts of the United States. Solar energy is generally a better alternative energy solution for these locations. However, much of the Midwest sees Class 2 winds at 30 m. Other locations across the globe at the same latitudes also experience similar wind regimes. Though a challenge to capture and utilize, these winds represent an untapped renewable energy resource.

2.3 Anatomy of a Wing or Airfoil

The airfoil or blade is the predominant moving part on any wind machine. It is the part that captures the kinetic energy of the wind and converts it to useful mechanical motion. Lift producing windmill airfoils or blades predate heavier than air flight by 800 years (Gipe, 2004). However, modern aerodynamics and computations have greatly accelerated the development and refinement of wind turbine airfoils. The cross section of a modern wind blade is similar to an aircraft wing. Figure 2 shows a cross section of a typical modern aircraft wing.

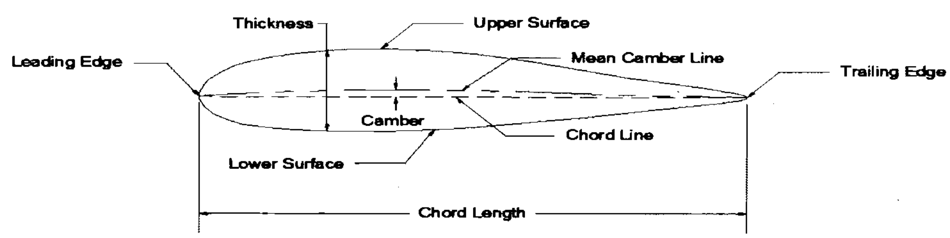

Figure 2: Cross section of a wing. *(Courtesy of Nathan Smith, 2010)*

The wing or airfoil has the *leading edge* which is the foremost point of an airfoil. This leading edge effectively separates the incoming airstream. The *trailing edge* is the rearmost point of an airfoil. The *chord line* is a straight line between the leading and trailing edges. Its length is referred to as the *chord length.* In heavily cambered wings, the cord line can extend through the exterior of the wing.

At the advent of powered flight, airfoils were heavily curved or cambered to imitate birds' wings (Craig, 2002). The *mean camber line* or simply the *camber line* is the line which connects all the center points of the interior of the wing. It runs midway between the upper and lower surfaces of the airfoil. *Camber* is the measure of curvature of the camber line in relation to the cord line. The *upper* and *lower surfaces* of the wing are the exposed areas on each side of the airfoil that interact with the air flowing around them.

For a given cross section of the wing or blade, a camber line can be drawn. If the half potion of the airfoil above the camber line is identical to the half portion of the airfoil below the camber line, then the airfoil is considered *symmetrical.* The airfoil is considered *asymmetrical* if the cross sections portions above and below the camber line are different in shape. The nuances in symmetry will affect airfoil performance.

2.4 NACA Airfoil Features

Airfoils used in earlier wind turbines were developed from aviation wings. Many of these aviation airfoils were researched and designed under the National Advisory Committee for Aeronautics (NACA). NACA was founded before the United States' entry into World War I and was dissolved in the late 1950s when the National Aeronautics and Space Administration (NASA) began. Airfoil features are specified by a series of numbers under the NACA system.

As Mathew (2006) writes, in the four digit NACA specification, the first number denotes the maximum camber of the airfoil at the chord line in percent of the chord. The second number locates the point of maximum camber from the leading edge of the airfoil in tenths of the chord. The third and fourth numbers indicate the maximum thickness in percent of the chord. For example, a NACA 2220 airfoil would have a maximum chamber of 2 per cent located at 0.2 times the chord length from the leading edge and the maximum thickness is 20 per cent of the chord.

2.5 The Power Equation

Various authors (Gipe, 2004; Wortman, 1983) have noted the lack of appreciation for the low energy density contained in wind as well as some of the exaggerated claims put forth from wind turbine manufacturers throughout the years. This lack of understanding, hype, and subsequent lack of performance has hindered wind power development.

Wind is a very diffuse energy source which requires some understanding before decisions regarding wind turbine design are undertaken. Tyree (2008) gives a very simple and clear derivation of the fluid power equation. The following derivation is primarily based upon his work.

The energy in moving air is in the form of kinetic energy (KE). Newtonian mechanics gives KE of a moving mass in the form of

$$E = \frac{1}{2} m v^2 \qquad (1)$$

where m is the mass of the object and v is the velocity. With a wind turbine, there are several unit masses of air moving perpendicular to the plane or area, A, swept out by the blades. Overall power, P_o, is the rate of energy movement per unit time, t or the rate at which energy is generated or consumed per unit time. Mathematically, P_o is the first derivative of energy taken with respect to time, *dE/dt*. This power is developed in wind turbines from the mass movement of the air so $P_o = dE/dt$ or

$$P_o = dE/dt = \tfrac{1}{2}\, dm/dt\, v^2 \qquad (2)$$

The next step is to quantify the amount of air flow associated with *dm/dt*. Given a unit time, t, the unit air masses, m, will have moved a distance of L. This can be used to arrive at two important results. The first result is that the first derivative of L with respect to t is dL/dt which equals velocity, v. Secondly, the volume of the air passing through A will be AL.

If the density of the air, ρ, is known or can be found, then the mass of the air moving through the plane A is m = ρAL. The mass movement rate, $dm/dt = \rho A dL/dt$ or

$$dm/dt = \rho A v \qquad (3)$$

Substituting (3) into (2) gives

$$P_o = \tfrac{1}{2}\rho A v^3 \qquad (4)$$

Equation (4) gives the ideal power in a fluid flow. However, wind turbines are limited by blade efficiencies, mechanical losses in transmissions, electrical losses in the generator and power electronics, and by the theoretical amount of energy allowed to be extracted from the breeze. Because of these losses and inefficiencies, two more variables are added to Equation (4).

The first variable is η which is a measure of the efficiency of the gearbox and electrical inverter and transformer. It takes into account all the friction, slippage, and heat losses associated with the interior mechanical and electrical components. Values for η can greatly differ between turbine models. Some smaller turbines are direct drive and lack a transmission while larger turbines have transmission and reasonably involved inverters and synchronizing gear. For a well designed, commercial turbine, η can reach around 0.70 but it is most often in the 0.40-0.60 range (da Rosa, 2009). However, experience shows that direct drive systems utilizing modern power electronics might see η values approaching 0.80.

The second variable is the power coefficient, C_p. The C_p is a measure of blade or airfoil efficiency. It takes into account the airfoil shape and the aerodynamic forces of lift and drag. The C_p expresses an airfoil's ability to transform the wind's kinetic energy into mechanical power which is delivered to a turbine's transmission or generator. A higher C_p is preferred over a lower C_p value.

These C_p values vary with turbine size. Longer blades allow designers more space to add chord and curvature to an airfoil which improves the C_p. Johnson (1985) writes that modern HAWTs and Darrieus VAWTs have C_p values ranging from 0.30 to 0.45. Gipe (2004) notes the large blades on commercial sized wind turbines can see C_p numbers in the upper 0.40s while smaller household size wind turbines have C_p values in the 0.10-0.20 range.

Placing these two variables, η and C_p into Equation (4) gives

$$P_n = ½ \rho A v^3 \eta\, C_p \qquad (5)$$

Equation (5) is the considered the power equation for wind turbines. P_n is the net power derived from the wind after accounting for losses and inefficiencies. It should be noted that though C_p can widely vary in Equation (5), it can never exceed 0.593 for a lifting airfoil. The reason is Betz's Limit and aerodynamic forces.

2.6 Aerodynamic Forces and Betz's Limits

There are four principle aerodynamic forces: lift, weight, thrust, and drag. Aside from a few experimental novelties utilizing the Magnus effect, wind machines, whether they are windmills or wind turbines, convert the kinetic energy of the wind into usable mechanical and electrical energy by either lift or drag. Weight also plays an important role in wind turbine physics especially concerning blade inertia, stress, and strain. Figure 3 shows the aerodynamic forces as they relate to an airfoil or blade.

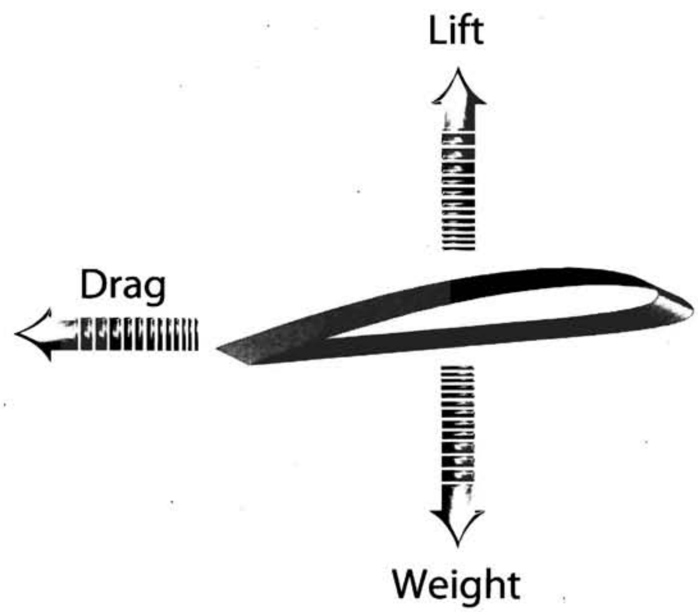

Figure 3: The aerodynamic forces on an airfoil. *(Courtesy of Ray Amerson Jr, 2010.)*

Very early wind machines in antiquity operated by drag. Starting about A.D. 1100 in Europe, wind machines started to utilize lift and the technology continued to be refined. Today, most modern wind turbines produce their power through the aerodynamic force called *lift.*

Any fluid flowing past a body exerts a surface force upon the body. Lift is defined as the component of this force which is perpendicular to the oncoming flow. As Cheremisinoff (1978) writes, by generating lift, the wind turbine can develop higher forces per unit area than by operating by drag. However, there is still some discussion and disagreement as to the causes of lift.

The popular theory of lift, sometimes referred to as the *equal transit times theory*, is often taught from elementary through high school in the United States. The theory attributes lift to the idea that air flowing over the curved upper surface of the airfoil must cover a greater distance than the air flowing under the less curved lower surface of the wing in the same amount of time. Because of the higher speed of the air over the upper surface, a zone of low pressure is produced in accordance with Bernoulli's Law. The higher pressure under the wing or airfoil exerts a force toward the low pressure zone and thus lift is created. Unfortunately, this theory does not explain why aircraft can fly upside down and how symmetric airfoils have been successful on both aircraft and wind turbines.

It is well known that an air molecule traveling across the upper surface of the wing travels moves at a higher speed and hence travels further than an air molecule traveling across the bottom surface of the wing (Craig, 2002; Kuethe and Chow, 1976;

Von Mises, 1959). A more complete explanation involves a combination of Bernoulli's Law and circulation theory along with classical Newtonian mechanics.

Many textbooks on aerodynamics will note that the Bernoulli's Law predominates at higher speed while the changing direction of the air over the airfoil generates a centrifugal force based upon Newton's 2^{nd} Law which causes a lifting force which predominates at lower speeds (Craig, 2002). .

There are many types of aerodynamic drag. Relating to airfoils, drag is considered those forces that oppose the motion of an object through the air. This opposition to motion is a factor for all wind turbines. However, drag as it relates to powering wind machines has another and more basic meaning.

A wind machine that is drag driven simply means the blowing wind "drags" or pushes the airfoils along. In this way, the blades of a wind machine acts like a ship's sails. In this manner, drag can be useful in powering wind machines. The traditional American windmill developed around 1850 is a drag device. Figure 4 shows an American windmill design dating to the 1870s.

Figure 4: Traditional multi-vane American windmill in Wyoming. *(Courtesy of author)*

A few smaller wind turbines today still operate by drag. Gipe (2004) notes Savonius rotor VAWTs are still being manufactured and used for small electrical generators in Finland. Many wind enthusiasts build drag type wind turbines as a first project because the design is straightforward and doesn't require the intricately curved airfoils of a lift machine. Still, most commercial wind turbines operate by lift and the reason lies in the research done by the German physicist Albert Betz.

Betz's Law was developed in 1919 and identified the maximum amount of energy that could be derived by a wind turbine. His research indicated that for an airfoil operating by lift, 16/27 or 59.3% of the available energy in the wind could be harnessed.

For an airfoil operating on drag, the ratio was a mere 4/27 or 14.8% (Gipe, 2004). This explains why most wind turbines operate via lift.

Because of lift, the blade tips of the wind turbine turn much faster than the speed of the wind blowing through the rotor. This comparison of blade tip speed to wind speed is known as the *tip speed ratio* (TSR). TSR is a very important design element in wind turbine engineering (Copper and Kennedy, 2005).

Higher TSRs equate to higher power output to weight ratios which aids the economics of the wind turbine (Cheremisinoff, 1978). Johnson (1985) notes that tip speed ratios of 1 or greater are preferred for electrical production and HAWTs can have tip speed ratios approaching 10. However, TSRs over 6 or so have a tendency to produce noise which can lead to complaints from nearby residents.

2.7 Horizontal Axis Wind Turbines

The majority of wind turbine design currently focuses on the horizontal axis wind turbines (HAWTs). Today, greater than 90% of all wind turbines are HAWTs (da Rosa, 2009) and virtually all wind turbines used for commercial generation are the HAWT variety (Gipe, 2004). Figure 5 shows a modern HAWT installation.

Figure 5: A modern 1.65 megawatt HAWT near Ellsworth, IL. *(Courtesy of author)*

The principal parts of a modern HAWT are the blades or airfoils which capture the kinetic energy of the wind via *lift* or *drag*. These airfoils can be made of metal, wood, plastic, fiberglass, or carbon fibers. The blades are attached to a *hub* and *nacelle* situated at the top of the *tower* or *mast*. The hub is usually a rounded, streamlined cap into which the blades are fitted. The nacelle is usually rectangular shaped and houses the electrical alternator, gearbox and turning *(yawing)*, and braking mechanisms. The tower or mast is the vertical support of the structure and is made of steel for commercial applications. Towers for commercial turbines are often 30 m, 50 m, or 80 m high and sit upon a reinforced concrete footing or wide base. Slightly above ground level inside the tower sits one or two cabinets which house the power electronics controlling voltage, phase, and frequency of the generated electricity. This energy is fed to a nearby transformer and sent to a nearby electrical collector substation which feeds the power to the electrical grid.

Modern HAWTs are currently favored for electrical generation for several reasons. First, the arrangement of the blades allows nearly their full area swept to always be interacting with the breeze. The HAWT's airfoils are twisted and shaped as propeller blades act as wings and not as walls to the wind. Because of their low solidity (ratio of blade area to the actual swept area), σ, a breeze is able to quickly blow through the path of the blades and turn the airfoils (Copper and Kennedy, 2005). This greatly aids the airfoils in the production of *lift*. Also, the blades of a HAWTs being perpendicular to a breeze improves the power coefficient (C_p) of modern HAWTs. Though very successful, the modern HAWT is not without criticisms or weaknesses.

A very common objection to wind farm development is the rhythmic noise from the rotation of the blades. Sources of this noise can vary from trailing edge blade noise relating to turbulence to the effect of unsteady loading noise caused by the change in wind velocity which is due to the presence of the tower and mechanical noise from the gearbox and yawing mechanism (Wagner, Bareib, and Guidati, 1996). The higher TSRs of HAWTs can exacerbate noise issues.

Empirical evidence shows that common large commercial HAWTs can output sound pressure levels ranging from 58 dBA to 109 dBA (Rogers, Manwell, and Wright, 2006). The lower end of the range is often just above ambient noise sound pressure levels in some rural environments and the sound pressure level drops off rapidly with distance. The upper end of the range is not seen in large modern turbines however smaller, older turbines from the 1980s can produce sound pressure levels over 100 dBA because of their high tip speed ratios. Most of these early turbines were installed in isolated areas where the population is low.

A second common objection concerns the aesthetics of large HAWTs. Though this topic is subjective by nature, it is often a very important issue during the planning stage of wind farm development. Many landowners fear that their property values will decrease if a wind farm is built near their property. Part of this fear is reduced by the $3,000-$5,000 annual lease that many rural landowners receive per turbine installed upon their property.

Some criticism has been brought about wind technology and the danger to avian species. Much of this concern stems from early wind farm construction in California. During the late 1970s and early 1980s, some farms were unfortunately sited in migratory bird paths. In light of these past mistakes, guidelines have already been developed by most states (Association of Fish and Wildlife Agencies, 2007). Current statistics shows that avian deaths due to wind turbines are approximately 0.02% of all the avian killed by other human built structures in the nation (Sagrillo, 2003). Massive construction of wind turbines nevertheless, have to be done carefully in order to protect wildlife.

Finally, there are three technical issues that demonstrate the limitations point of HAWT design. First, HAWTs cannot operate in high winds. Generally, the large turbines must yaw or turn their blades out of the wind and apply a brake when wind speeds reach above 25 m/s or about 55 mph. Unfortunately, the power available in any wind is directly proportion to the velocity of the wind cubed so many large turbines are unable to harness this power. HAWTs operate best on rolling hills, in mountain passes, or offshore where there are few obstructions. HAWTs are not designed for the turbulent winds found in urban environments. Finally, the size of the HAWT is reaching an upper limit. Massive 5 MW wind turbines with blade diameters of 126 m (over 400 ft) currently hold the title as the largest wind turbines. Though this is not the maximum structural or material limit, an end is in sight (Marsh, 2005). It is doubtful that reliable 10 MW HAWTs will ever be built. In light of all these criticisms and disadvantages, a renewed interest has been shown in vertical axis wind turbines, VAWTs.

2.8 Vertical Axis Wind Turbines

In VAWT designs, the air scoops or airfoils rotate perpendicular to the direction of the wind. Both HAWTs and VAWTs share several common parts though the location and arrangement of these parts vary depending upon the turbine type. Figure 6 shows a typical HAWT and an H-rotor Darrieus VAWT.

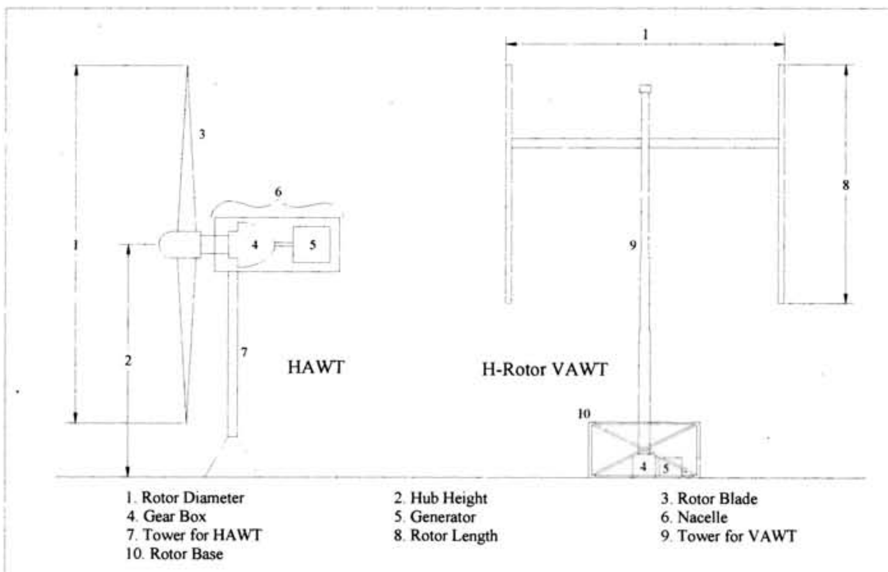

Figure 6: Comparison of a HAWT and an H-rotor Darrieus VAWT.

(Courtesy of Nathan Smith, 2010)

As Gipe (2004) notes, there are two principle designs of VAWT, the Savonius type and the Darrieus type. Darrieus VAWTs have been designed in several configurations. The two configurations that show the greatest promise are the troposkein and the H-rotor Darrieus types though Savonius rotors are still used for electrical generation on some small turbines.

S. J. Savonius, a Finnish engineer, created his first VAWTs in 1922 (Peace, 2004). As Cheremisinoff (1978) points out, a typical Savonius design uses two S-shaped blades or cups for the rotor though modern versions often incorporate more blades. These VAWTs are primarily drag devices in which the wind blows into one of the cups or buckets. The exterior of the buckets are curved, thereby cutting down on drag. More thrust is produced in the bucket being pushed downwind than the drag generated by the other bucket traveling upwind so the device rotates. Johnson (1985) writes that Savonius rotors are primarily drag turbines since their tip speed ratio is generally less than 1. This low tip speed ratio greatly limits their use in electrical production. Figure 7 shows a Savonius rotor turbine with four blades.

Figure 7: A homebuilt four bladed Savonius VAWT. *(Courtesy of author)*

Savonius turbines have high starting torque but a low tip speed ratio which translates into lower power outputs for a given rotor size (Cheremisinoff, 1978). Also, Savonius rotors primarily operate by drag so this greatly limits their usage in large scale electrical generation (da Rosa, 2009). According to Johnson (1985), a Savonius style wind turbine has a C_p of around 0.30 which is considered useful and reasonably efficient but its low tip speed ratio makes it better suited for operation of mechanical pumps. Though having a low tip speed ratio is a major disadvantage for electrical production, Savonius VAWTs have two advantages in that they are simple and inexpensive to construct and are self starting, even in very low wind speeds of 2 m/s.

In 1931, Georges Darrieus patented his VAWT in the United States (Bernhoff, Eriksson, and Leijon, 2006). Instead of cups catching the wind, the Darrieus VAWT uses two or three curved blades which have a cross section similar to an airplane wing hence it is a lift producing turbine. Turbines operating on lift are able to harness 16/27 the available energy from the wind according to Albert Betz.

The blades of a traditional Darrieus turbine are curved and joined together at the top and bottom while being bowed outward in the middle. This shape is called a *troposkein*, Greek for turning rope (Johnson, 1985). Figure 8 shows a traditional Darrieus VAWT.

Figure 8: A traditional Darrieus troposkein VAWT. (*Courtesy of Wikipedia)*

Johnson (1985) further notes that the Darrieus turbine has several advantages in that its blades operate under nearly pure tension so they can be constructed of lightweight material. Like most VAWTs, its gearbox and alternator are located near the ground facilitating ease of maintenance. The C_p of a traditional Darrieus is comparable to that of many modern HAWTs. However, Darrieus models are not self starting and the manufacture of their blades is a challenge because of the bent shape. This adds expense to the turbine.

An H-rotor Darrieus is another type of VAWT. In its simplest form, the rotor assembly is comprised of two vertical airfoils or blades. One blade is mounted at each end of a horizontal support. This construction is then mounted to a tower via a bearing located in the center of the horizontal support. This forms the “H” shape. The airfoils are free to interact with the wind (Marsh and Peace, 2005). Unlike the Savonius design, the H-form Darrieus generates most of its power through lift, not drag. Because of this and its higher C_p, a Darrieus makes a better VAWT choice for extracting power from the wind (Bernhoff, Eriksson, and Leijon, 2006). Figure 9 shows an H-rotor Darrieus VAWT.

Figure 9: An H-rotor Darrieus VAWT. *(Image courtesy of Wikipedia)*

Though both general categories of wind turbines are useful, HAWTs have so far dominated the power field. The dynamics of HAWTs are well understood and designers have been very successful increasing the size and efficiency of these turbines. However, VAWTs are again being researched because of some of their inherent design benefits.

Because of their vertical symmetry, VAWTs do not require expensive yaw controls to turn their blades into the wind. Fartaj, Islam, and Ting (2006) notes that this lack of yaw control greatly simplifies the overall VAWT design. VAWTs generally can operate in higher wind speeds and because VAWTs can take wind from any direction they are considered omni-directional. These features allow for little power loss during the time it would take to turn a HAWT into the wind or with deal with changes in the wind's direction (Datta, Leung, and Roynarin, 2002).

As noted briefly before, gearboxes and generators can be mounted on the ground with the VAWT design instead of on top of large towers. Furthermore, VAWT blade design and fabrication is usually easier than HAWT blades (Cheremisinoff, 1978). Bernhoff et al. (2006) note that the blades of an H-rotor wind turbine are even easier to construct than the blades of a Darrieus VAWT since the H-rotor blades are straight with little curvature. These features allow for a less expensive, less obtrusive, and quieter wind turbine.

However, VAWTs possess a major disadvantage. The types of VAWTs best suited for electrical production are not self starting and require additional mechanisms to start their blades spinning in a breeze (Mathew, 2006). Gipe (2004) notes that fixed pitch blades on most VAWTs can not drive the rotor up to operating speed from a stand still unless the blades are parked in exactly the right position relative to the wind. Though variable pitch blades on some VAWT designs can enable such machines to start, the results have been expensive and complicated mechanisms (Gipe, 2004).

This is a serious problem as machines are designed and built according to a budget and return on investment (ROI). Starting mechanisms add initial cost and continued maintenance to a turbine.

The aim of this research is to identify self starting provisions that can be incorporated into the design of an electricity producing VAWT. This will be a challenge as it is not known if these changes will work on all VAWTs. It is uncertain if the performance characteristics of modified VAWTs will be improved.

Generally, the inclusion of these provisions raises additional questions as to how the performance of the VAWT will be affected. How well will these provisions work?

How will efficiency of the turbine be affected? How costly are these improvements? All these questions stem from solving the central problem of creating a reliable and inexpensive starting mechanism for VAWTs.

2.9 Improvements for VAWT Designs

Recently, some researchers have undertaken efforts to develop a self starting VAWT by incorporating an inexpensive variable pitch device for the blades (e.g., Cooper and Kennedy, 2005; Tristanto, 2005). The H-rotor Darrieus wind turbine is well suited for these self starting experiments. Its blades are easily fabricated and the free area along the height of the tower and along its horizontal arms to the airfoils allows for the mounting of extra machinery and as well as maintenance access. Furthermore, its tip speed ratio is high so that is useful for electrical production.

The force required to start a wind turbine is called its *start up torque.* It is well known in engineering fields that the start up torque of any motor or generator is large compared to the running torque when device is spinning. By changing the *pitch* or the angle that the airfoil or blade makes with the wind, a change of lift is experienced. By changing the blades' pitch of an H-rotor Darrieus, it is hoped that sufficient lift is generated to equal or surpass the start up torque and thus create a self starting H-rotor VAWT.

Cooper and Kennedy's (2005) research focused on utilizing gears and sprockets to restrict blade pitch to 180°. Tristanto's (2005) design went further and allowed 270° and 360° of pitch variation. Allowing so much pitch variation, indeed rotation, requires special attention to the choice of airfoil or blade shapes.

Lift is the primary force generated by the blades of HAWTs and on all Darrieus VAWTs. Often, the blade or airfoil has an asymmetric shape in order to maximize lift. In general, the upper or outer surface of a wind turbine blade will be curved while the bottom or inner surface is less curved. According to Craig (2002), one theory of lift sees air slice around the blade and form a circulatory motion. This circulation or vortex increases with increasing wind speed and helps to create an area of lower pressure along the curved portion of the blade relative to the airstream passing along the flat portion of the airfoil. This pressure differential between low and high pressures results in a force known as lift in the direction of high to low pressure. It is lift that provides for the much higher tip speed ratios which are desirable for electrical generation. However, an asymmetric airfoil can loose much of its lift if widely rotated through varying angles of attack.

Kawachi, Sakaguchi, and Sunada (1997) confirmed that certain symmetric airfoils could produce sufficient lift compared to the standard, streamlined airfoils. These flatter blades are far more symmetric than standard airfoils so they would be better suited for use with widely variable pitch mechanisms. Both Cooper and Kennedy (2005) and Tristanto (2005) used these airfoils as a starting point for their research.

Though both research groups succeeded in producing a self starting H-rotor Darrieus, their results were not completely satisfactory. In the case of Tristanto (2005), her model wind turbine had a C_p of only around 0.25. Cooper and Kennedy (2005) managed to realize a C_p value of 0.25 but found their tip speed ratio to have fallen into a range of 0.2 through 0.8. In effect, Cooper and Kennedy took a lift producing H-rotor Darrieus and by varying the pitch, gave it the performance of a Savonius VAWT.

However, their collective research proves that a self starting H-rotor is possible. Is it possible to combine the Savonius rotor and a Darrieus rotor into a single structure?

A combined Savonius-Darrieus VAWT would have many advantages over an individual Savonius or an individual Darrieus rotor (Biswas, Gupta, and Sharma, 2008). A Savonius produces high torque which would be useful in self starting. A Darrieus rotor has a high tip speed ratio useful for electrical generation. However, Biswas et al. note that research on combined Savonius and Darrieus rotors is very scarce.

Biswas et al. (2008) developed a three bucket Savonius rotor and placed it on the central shaft of a traditional Darrieus. Various geometries for the Savonius rotor were tried. Some impressive results were obtained and their research demonstrated a self starting VAWT.

By allowing a 16% air gap between the buckets of the Savonius rotor attached to the Darrieus shaft, C_p of 0.3403 was seen along with a tip speed ratio of 0.305. However, by removing the air between the buckets of the Savonius rotor and combining this with a Darrieus rotor, an incredible C_p of 0.51 was realized with a tip speed ratio of 0.62 (Biswas et al., 2008). Though the tip speed ratio is a still a little low for use as an electrical generator, the research demonstrated a simple way to enable a Darrieus VAWT to be self starting and achieve high operating efficiencies. Their work demonstrated a path for future research but higher TSRs are necessary for significant electrical generation. Figure 10 shows a hybrid Savonius/Darrieus VAWT.

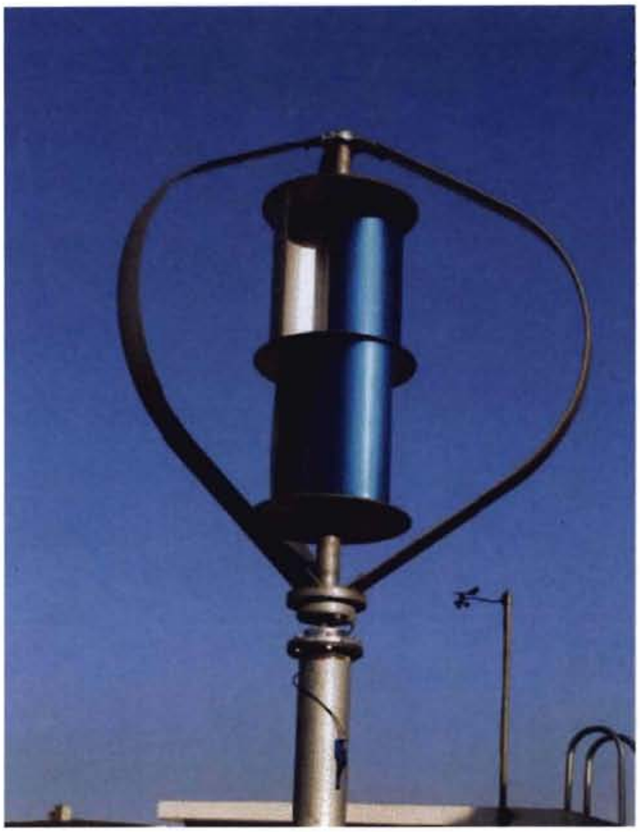

Figure 10: A hybrid Savonius/Darrieus VAWT. (*Courtesy of Wikipedia)*

A researcher should expect such a hybrid VAWT system to achieve relatively high C_p values because of the low solidity of the H-rotor style. The tip speed ratio should be close to 1 and ideally, a little above it. Lift is needed to provide the high rotational speeds favored in electricity production so the use of highly asymmetric or curved airfoils or blades need to be used.

Efficiency still is a major drawback to the use of VAWTs in commercial power production. State of the art HAWTs can realize coefficient of performance (C_p) values approaching 0.50 while the best VAWTs see C_p numbers a little better than 0.40. Johnson (1985) notes that most VAWTs average C_p values in the 0.30s. Secondly, VAWTs have traditionally have not been located on towers. This often limits the turbine's access to higher winds and thus higher electrical production. Historically, VAWTs cost more to operate and maintain than HAWTs. The Flo Wind Company supplied a fleet of several hundred VAWTs located in the Californian mountain passes of Altamont and Tehachapi which operated for 20 years before maintenance costs caused the machines to be retired (Sagrillo, 2005). As a rule, turbines are expected to have a 25 to 30 years lifespan.

Finally, traditional Darrieus rotors are not self-starting under most wind conditions and the manufacture of their blades is a challenge because of the complex shape which adds expense to the turbine. Research and development of H-rotor Darrieus models is seeking to overcome both the self-starting and manufacturing issues of the traditional "eggbeater" style.

The (Darrieus) VAWT is not self-starting and typically uses the generator as a motor to spin the blades up to operating speeds (Berg, 1996). Exceptions do exist as Darrieus turbines can self-start under certain conditions. The principal issues affecting self-starting capabilities are the electromechanical load upon the VAWT and the shape and number of airfoils.

Darrieus wind turbines have difficulty in self-starting in most normal wind regimes. However, evidence shows that a Darrieus turbine using fixed geometry symmetrical airfoils can self-start in the field during atmospheric gusting (Dominy, Lunt, Bickerdyke, and Dominy, 2006). Evidence shows that lightly loaded VAWTs equipped with symmetrical, NACA (National Advisory Committee for Aeronautics) 0012 airfoils will self-start in wind speeds under 10 m/s, 22.4 mph (Dominy et al., 2006).

As Tangler (2000) notes, the constant chord VAWT blades adversely affect blade efficiency and self-start capability. Darrieus type VAWTs have historically used symmetric airfoils from the NACA 4-digit series, mostly NACA 0012, 0015, and 0018 which were developed for aviation applications (Islam, Fartaj, and Carriveau, 2008). These airfoils were used because there is much performance data for them. However, the main problem with using these symmetric airfoils is their low starting torque at low speeds (Islam, Fartaj, and Carriveau, 2008).

Research into new airfoils for VAWT applications is somewhat increasing. The general direction for Darriues H-rotor design points to using asymmetric airfoils in place of symmetric airfoils. Islam, Fartaj, and Carriveau (2008) state that it is better to use a high lift and low drag asymmetric thick airfoil for low speed operation typically encountered by SBVAWTs. These thick airfoil shapes have several advantages for smaller SBVAWTs including improved performance and increase in starting torque (Islam, Ting, & Fartaj, 2007). Continued research and development with thick airfoil shapes is warranted with a focus upon developing a self-starting SBVAWT.

2.10 Materials for VAWT Airfoils

Airfoil materials for SBVAWTs must be judiciously chosen because wind turbines operate under a variety of forces and weather conditions. Berg (1996) states that wind turbines are fatigue critical structures subjected to combinations of wind, gravity, and gyroscopic loadings. At rotation rates of 30-60 rpm, the turbine blades must withstand at least 10^9 cycles during a 30 year lifetime which is 100 to 1000 times more cycles than a typical transport aircraft is designed to withstand.

Aluminum blades fabricated by extrusion and bending have often been used on VAWTs. Though reasonably inexpensive to manufacture, aluminum is not the best choice for VAWT blades. The main problem with using aluminum alloy is its poor fatigue properties and its allowable stress levels in dynamic applications decrease rapidly at increasing number of cyclic stress applications (Islam, Ahmed, Ting, and Fartaj, 2008).

Wood is a better choice for VAWT blades. Many smaller, homebuilt HAWTs use wooden airfoils. As a building material, wood is readily available and has good fatigue properties as well as a relatively high strength-to-weight ratio but has moisture stability issues (Islam, Ahmed, Ting, and Fartaj, 2008). It is easily shaped and wood can be coated to prevent moisture penetration. It is a good candidate for small, experimental VAWT airfoil research.

Fiberglass composites or fiber reinforced plastics are another possible material for VAWT airfoils. These composites have low density, good mechanical properties, excellent corrosion resistance and versatility of fabrication methods (Islam, Ahmed, Ting, and Fartaj, 2008). Fiberglass composites already see widespread in HAWT blades where their strong performance makes them the material of choice. Fiberglass composites are another strong candidate for small, experimental VAWT research.

The literature research indicates that a self-starting Darrieus turbine can be built. Using thicker, asymmetric airfoils appears to be one of the more promising research avenues. An H-rotor Darrieus made of wood and plastic covering is supported by the manufacturing skill and accessible workshops associated with this project. With these parameters, construction on a SBVAWT can begin.

CHAPTER 3

Research Methods

3.1 Goal of Research Plan

The goal of comparing a SBVAWT and a HAWT guided the research methodology. Because of this goal, the research was divided into three key construction components. The first component was the design and construction of a HAWT with a swept area of 1.50 m^2. The second construction component was the small scale design and testing of a suitable VAWT airfoil for use on larger SBVAWT. Thirdly, a VAWT with a swept area of approximately 1.50 m^2 was built based upon the results of the small scale design and testing. Construction of the HAWT began first.

3.2 Construction of the HAWT

The HAWT used a set of three high performance blades. The blades were made of molded ABS plastic and were approximately 66 cm long. Two McMillian Electric Company Model S3365B2938 permanent magnet DC treadmill motors were used in building the HAWT and the VAWT.

The HAWT motor was housed in a 10 cm diameter Schedule 40 polyvinylchloride (PVC) pipe while a 2.5 cm square length of steel tubing was used for the nacelle base. A 30 cm x 30 cm tail vane was fashioned and bolted to the square steel tubing. Figure 11 shows the completed HAWT and the WindWorks wind anemometer readied for testing.

Figure 11: The 1.50 m^2 research HAWT with Windworks Anemometer. (*Courtesy of author)*

3.3 Data Collection and Measuring Equipment

Electronic data acquisition was needed for both voltage and wind anemometry. A WindWorks anemometer with on-line data logging of the wind speed and direction was used. The cup anemometer and wind vane was installed on a 1.2 m piece of 3.8 cm diameter Schedule 40 PVC pipe. The anemometry software was installed on a laptop computer.

A model HWM 100US handheld anemometer by ELV Electronics Limited was used as a secondary anemometer. This cup anemometer also included a thermometer which was used to measure temperature at the testing location.

An EL-USB-3 Voltage Data Logger by Lasco Electronics was the primary means of voltage measurement and storage. An inexpensive handheld digital voltmeter was also employed for small model testing as well as a secondary unit for the full scale testing. This was a model DT-9208AL Digital Multimeter from All Electronics.

The mass of the small scale and full size airfoils were also recorded with the results shown in Table 1. An Explorer Pro Model EP8101C electronic scale by Ohaus was used to weigh each individual blade. This scale was calibrated to Illinois Department of Transportation (IDOT) standards and accurate to one-tenth of a gram.

3.4 Airfoil Selection

Much research went into identifying potential asymmetric airfoils that would be able to produce sufficient torque allowing a SBVAWT to self start. An extensive literature review yielded some useful articles and information. However, the scholarly information and research available on VAWTs is much less than the scholarly information available on HAWTs at the time of this writing.

Islam et al. (2007) researched the Selig S1210 airfoil and developed their own M1-VAWT1 airfoil. These two airfoils showed significant promise and were chosen to be built. A third asymmetric airfoil, the NSS-1, was independently developed at Lake

Land College by the author and his engineering technician, Nathan Smith. The NSS-1 was based upon noted desirable features for SBVAWT airfoils. These three different blades were then built as 15 cm models and tested on the same tower with the same resistive load and motor. The *cut in speed* and the generated voltage was noted in these tests. Cut in speed is defined for these tests as that wind speed at which the wind turbine starts and is able to complete one 360° revolution. The airfoil that showed the lowest cut in speed was then built in full size (1.27 m) for testing against the HAWT.

For comparison of the VAWT with the HAWT, the VAWT were of similar swept area and attached to a similar motor and similar load. Again, cut in speed and the voltage was measured. These comparison tests between a SBVAWT and a HAWT involved electronic data logging of both the anemometry and the generate voltage.

3.5 Airfoil Construction

The construction of all the SBVAWTs was the most challenging problem. Lacking a substantial workshop, materials had to be worked with small hand tools and band saws. Originally, the plan called for the small scale model airfoils to be built entirely out of balsa wood and glue with hardwood dowels as the horizontal support. The airfoils were to be built of 8 cm solid cross sections of balsa wood and then glue together. These airfoils were envisioned to be around 60 cm in length.

Several attempts were made build these airfoils but the tools available were unable to produce an airfoil of uniform shape, curvature, and chord over 25 cm in length. Even with extensive sanding, the resulting blades showed unequal curvature and shape.

Figure 12 shows an early airfoil under construction. Given the failure of building 60 cm airfoils out of balsa wood, another method was examined.

Figure 12: An early attempt to build an S1210 airfoil. *(Courtesy of author)*

The principal failure of using a solid wood cross section was that the airfoil showed erratic curvature after approximately 15 cm in length. The decision was made to limit small airfoils to about 15 cm in length and make these small test blades out of some type of plastic foam with hardwood dowel supports. This would facilitate faster construction as plastic foam is easier to cut and contour and its light weight would reduce blade inertia making a very breeze responsive airfoil.

Initially, very dense extruded foam provided by Eastern Illinois University was used in making the 15 cm airfoils. Though very successful in cutting and shaping, the material was very dense and heavy. A test model turbine did not spin well due to the airfoils' inertia. Also, the dust from cutting this dense extruded foam proved to be very challenging to both sinus and skin alike. Next, extruded Styrofoam available in 1.2 m by 2.4 m sheets was tried.

The extruded Styrofoam was cut into 15 cm strips with strip thickness of 7.6 cm. These strips were then further cut and formed into the three types airfoils used in small model testing: the S1210, the M1-VAWT1, and the NSS-1. Each airfoil was formed by two pieces of Styrofoam so that the overall length was 15.2 cm. Figure 13 shows the three different types of blades before the attachment of the horizontal supports.

Figure 13: The S1210, M1-VAWT1, and NSS1 small model airfoils. *(Courtesy of author)*

Next, three blades of each type were fitted to a wooden shaft 2.5 cm in diameter by way of a single 0.47 cm horizontal support. This wooden shaft was directly attached to a Matsushita model MMT-3RE2MJ 13.2 V DC motor. The shaft and motor were mounted upon a 0.61 m Schedule 40 PVC tower. A 0.10 Ω, 10 W power resistor was used to provide a load for these tests. The total resistance of the system was measure to be 22.8 Ω at 71.2 °F. Figure 14 shows the tower, motor, and shaft fitted with a set of blades

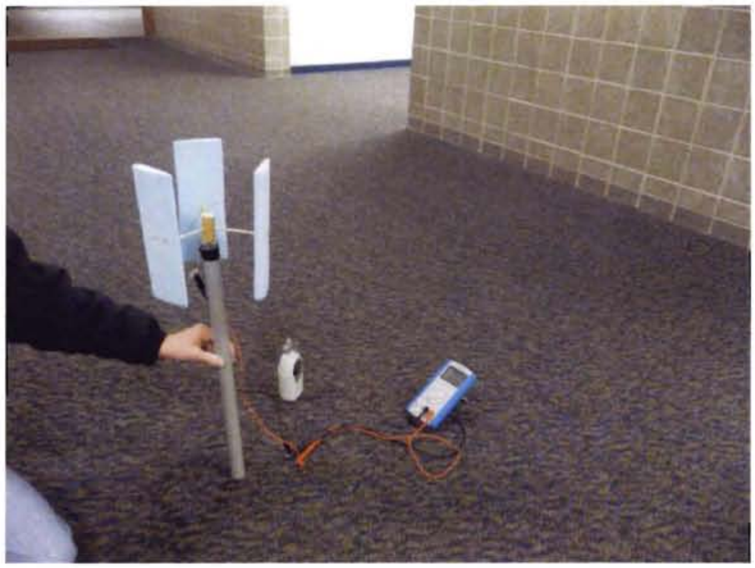

Figure 14: A 15 cm wind turbine model being readied for testing. *(Courtesy of author)*

3.6 Small Airfoil Testing

Each test was conducted in an open area approximately 3.6 m wide and 7.6 m long. The weather conditions during available testing dates excluded exterior trials. This was deemed acceptable given the nature of the small scale testing. The testing involved a carpet fan as the wind source. The HWM 100US handheld anemometer was placed approximately 15 cm (6 in) to the immediate side of the turbine so as to measure the wind speed and the DT-9208AL multimeter was connected across the power resistor to measure generated voltage. The fan was started at low speed and the resulting wind field was allowed to come to a steady state condition.

Each model wind turbine was stationed approximately 1.5 m from the fan with its blades locked. When it was centered in the wind field, the blades were released and the turbine was observed to see if it self-started. If it self-started, its rotation was then monitored. The criteria of this testing was starting motion and at least one complete 360° revolution. If the turbine started and operated at 1.5 m from the fan, it was then stopped and moved further away from the fan. The process was then repeated at this more distant location. A location corresponding to each turbine's cut-in speed was established. At this point, several tests were made recording cut in speeds and the generated voltage.

Figure 15: Testing arrangement of small wind turbine and carpet fan. *(Courtesy of author)*

3.7 Full or Large Scale Airfoil Construction and Testing

The SBVAWT airfoil displaying the lowest cut in speed during the small scale testing was chosen to be built as a full size blade for comparison with the HAWT. The swept area of the HAWT calculated to 1.50 m^2 so the swept area of the SBVAWT needed to be similar. However, the swept area of a SBVAWT is length of blades multiplied by diameter and not π multiplied by the square of the radius. This meant finding a way to construct larger airfoils on the order of 1 m in length. The rib and spar method was employed.

A local business was discovered with a computer controlled carbon dioxide laser. An AutoCAD file of the best performing SBVAWT cross section was provided and approximately 60 ribs were cut from 0.32 cm Baltic birch. Figure 16 shows the birch ribs.

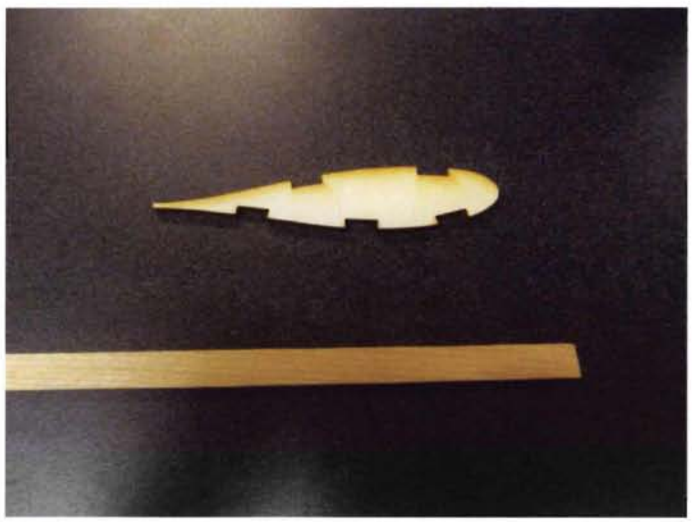

Figure 16: Cross section of full size SBVAWT airfoil. *(Courtesy of author)*

Additionally, three 7 cm and three 3.5 cm sections of the dense foam provided by EIU were cut to act as the middle rib and bottom rib for each blade. The two 0.95 cm horizontal supports were placed in the middle rib while one 0.32 cm horizontal support was placed in the bottom rib for better stability. Figure 17 shows construction of the full size airfoils.

Figure 17: A full size airfoil under construction. *(Courtesy of author)*

The airfoils were covered with 91.4 cm long and 30.5 cm wide strips of self adhesive plastic sheets known as trim sheets. MonoKote trim sheets by Top Flite were used in the construction of the SBVAWT. Though these self adhesive strips are primarily used for patching wings and fuselages of radio controlled (RC) aircraft, they proved a very speedy, serviceable, and cost effective method of covering the blades. At the end of the full scale SBVAWT construction, the airfoils measured 1.27 m long and when attached to the center shaft circumscribed a circle of 1.2 m diameter.

3.8 Testing the Full Size Turbines

Weather conditions forced the interior testing of the full sized HAWT and SBVAWT turbines. Testing was performed in one of the large agriculture implement repair labs at Lake Land College in Mattoon, IL. The WindWorks anemometer was installed in a mount to the immediate side of the turbines and the EL-USB-3 Voltage

Data Logger was activated. Both pieces of data logging equipment were synchronized to the laptop computer's clock and were set to record readings every 10 seconds. The handheld HWM 100US anemometer was used as a secondary anemometer. The DT-9208AL multimeter was used to measure the system's total resistance. Due to interior testing, a table measuring approximately 76 cm high was brought in and two carpet fans were placed atop it to provide an adequate wind field.

The original experimental plan for the full sized wind turbines called for them to be located parallel with each other outdoors with a distance of 3-4 m between them. The anemometer would be placed in the space between the turbines. This plan had to be modified because of interior testing location and the limited amount of volume generated by the carpet fans.

The modified experimental plan called for individually testing the turbines. Each turbine was situated where the wind speed measured only 1 m/s (about 2.2 mph). The carpet fans were then moved closer if the turbine didn't self start. The cut in speed was found very quickly by using this process. The wind speed and the generated voltage were recorded once the general location of the cut in speed wind was found.

The SBVAWT was tested first followed by the HAWT. The start up of the HAWT produced an interesting discovery. The testing would end in partial success and produce some promising results. Figure 18 shows the experimental setup with the carpet fans, SBVAWT, and anemometer. Figure 19 shows a closer view of the SBVAWT and the anemometer.

Figure 18: Experimental setup for the SBVAWT. *(Courtesy of author)*

Figure 19: The SBVAWT and the anemometer. *(Courtesy of author)*

CHAPTER 4

Results and Discussion

4.1 Small Model Testing Results

The 15 cm (six inches) extruded Styrofoam airfoils of the S1210, NSS-1, and MI-VAWT1 were built and then weighed immediately prior to testing. Each airfoil or blade was attached to a 15 cm (six inches) wooden horizontal support of 0.31 cm (1/8 inch) diameter. The results are shown in Table 4.1.

	S1210 Airfoil	NSS-1 Airfoil	MI-VAWT1 Airfoil
Blade 1	11.2 g	11.5 g	13.1 g
Blade 2	11.4 g	11.0 g	12.7 g
Blade 3	12.6 g	11.0 g	12.1 g
Average Mass	11.7 g	11.2 g	12.6 g

Table 4.1 15 cm airfoil masses

Each set of airfoils was tested on a 0.61 m Schedule 40 PVC tower. Kirke (1998) notes the importance of testing a VAWT in different positions since lift will be affected by the positions of the blades relatively to the airstream. *Position 1* refers to an airfoil lying in front of the oncoming wind and acting as a wall. *Position 2* refers to a configuration where two blades form a sort of funnel for the oncoming wind. In this position, the third airfoil is perpendicular to the wind but at the furthest point downstream on the turbine. Figure 20 shows a SBVAWT in Position 1 while Figure 21 shows a SBVAWT in Position 2.

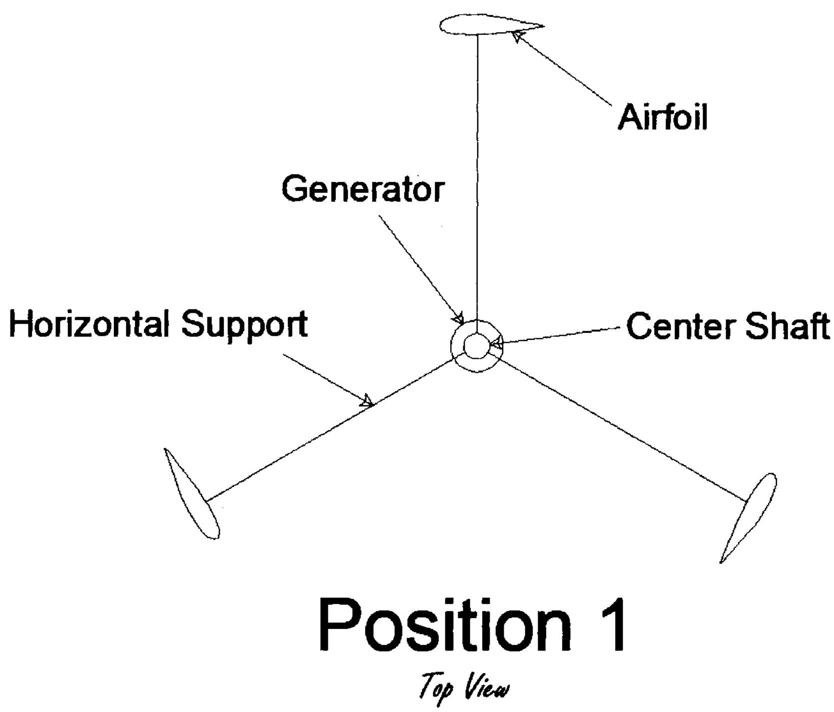

Figure 20: Blade Position 1 for SBVAWT testing. *(Courtesy of Nathan Smith, 2010)*

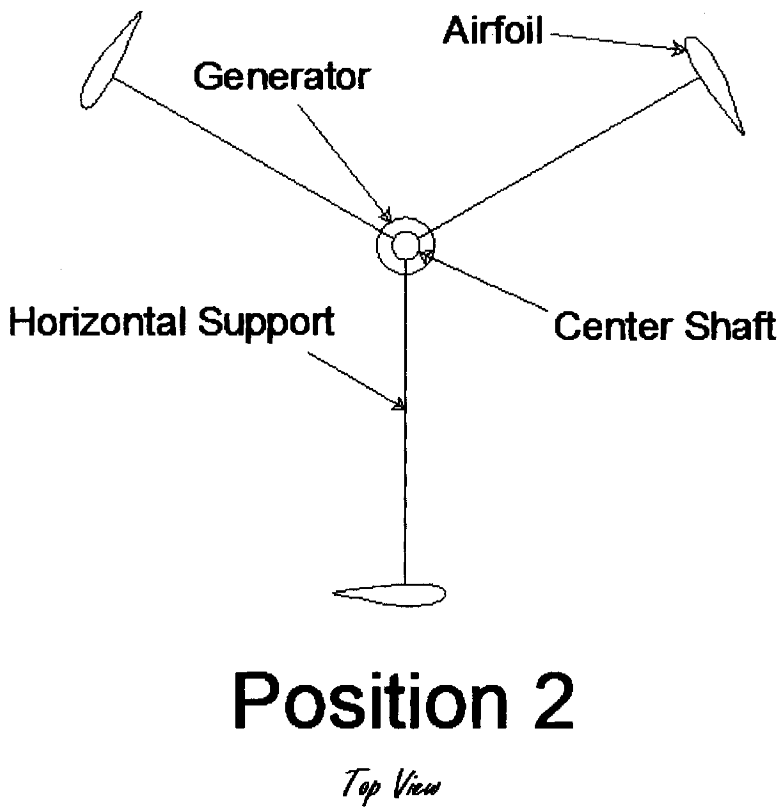

Figure 21: Blade Position 2 for SBVAWT testing. *(Courtesy of Nathan Smith, 2010)*

Four tests were performed on each airfoil. The results of the cut in speed and voltage for Position 1 are shown in Table 4.2 while the results for the cut in speed and voltage for Position 2 are shown in Table 4.3. Note, speeds are given in m/s while voltage is measured in volts for both tables

Airfoil	**Cut in 1 m/s**	**Voltage 1**	**Cut in 2 m/s**	**Voltage 2**	**Cut in 3 m/s**	**Voltage 3**	**Cut in 4 m/s**	**Voltage 4**
S1210	3.7	1.4	3.3	1.2	3.6	1.3	3.8	1.1
NSS-1	1.0	0.6	1.1	0.6	1.6	0.6	1.9	0.4
M1-VAWT1	0.9	0.6	0.7	0.5	1.2	0.5	0.6	0.2
Column Averages	**1.9**	**0.9**	**1.7**	**0.8**	**2.1**	**0.8**	**2.1**	**0.6**

Table 4.2 15 cm airfoil testing with blades in Position 1

Airfoil	**Cut in 1 m/s**	**Voltage 1**	**Cut in 2 m/s**	**Voltage 2**	**Cut in 3 m/s**	**Voltage 3**	**Cut in 4 m/s**	**Voltage 4**
S1210	2.3	0.7	0.4	0.2	0.5	1.0	1.0	0.2
NSS-1	0.9	0.1	1.0	0.3	1.0	0.2	0.7	0.2
M1-VAWT1	0.3	0.3	0.7	0.3	0.8	0.2	1.1	0.2
Column Averages	**1.2**	**0.4**	**0.7**	**0.3**	**0.8**	**0.5**	**0.9**	**0.2**

Table 4.3 15 cm airfoil testing with blades in Position 2

During these small scale tests, the M1-VAWT1 and the independently designed NSS-1 performed very similarly. The M1-VAWT1 gave slightly better low speed results and was chosen to be the airfoil to compete with the HAWT. M1-VAWT1 was designed by Islam, Ting, and Fartaj (2007) utilizing the best design features to enhance Darrieus rotor performance. Given the M1-VAWT1 marginally better performance and its pedigree, it was chosen for the full size comparison testing.

4.2 Full Scale Testing Results

The full scale turbine testing and comparison between the HAWT and SBVAWT was also performed indoors because of inclement weather. Some technical issues plagued the experimental setup, especially the initializing of the WindWorks anemometer. The wind speed data collected by the WindWorks anemometer was saved to a website. It was unable to be retrieved despite several attempts. The HWM 100US anemometer was used as a backup anemometer. The EL-USB-3 Voltage Data Logger was activated successfully and without incident.

The SBVAWT was first tested for cut in speed. During this initial test, it was discovered that screw hole that attaches the wooden center shaft to the DC generator had become worn or “hollowed out”. The turbine would operate but only with a wobble that grew more pronounced as testing continued. Because of this wobble, a certain orientation of the turbine would want to start rotating on its own but when it achieved a partial revolution, the turbine had a difficulty because it was fighting the “uphill portion” of the wobble.

Some small wooden toothpicks were used to better balance the turbine on the generator's shaft so as to perform at least the self starting and cut in speed tests. This was partially successful though power comparison tests with the HAWT could not be attempted because of the necessity of higher rpm operation. Nonetheless, the makeshift repairs allowed sufficient cut in speed testing of the SBVAWT though some play in the shaft remained. Table 4.4 shows the cut in speed for the VAWT while its blades were in Position 1. Table 4.5 shows the cut in speed for the VAWT while its blades were in Position 2. It should be noted that the whole SBVAWT rotor assembly weighed 1,472.2 g and that the total system resistance was 15.4 Ω.

Test Number	**Cut in speed (m/s)**
1	1.3
2	1.1
3	1.3
4	2.5
5	2.2
6	1.0
7	1.5
Average	**1.6**

Table 4.4: Cut in speed of SBVAWT with blades in Position 1

Test Number	Cut in speed (m/s)
1	1.0
2	1.5
3	1.2
4	1.1
5	1.3
6	2.5
7	1.1
Average	**1.4**

Table 4.5: Cut in speed of SBVAWT with blades in Position 2

Next, the HAWT was tested for its cut in speed and its results are recorded in Table 4.6. The HAWT's rotor assembly weighed 1,136.1 g and used the same power resistor as the SBVAWT as an external load. This system's total electrical resistance was 18.2 g.

Test Number	**Cut in speed (m/s)**
1	1.8
2	1.5
3	1.7
4	1.7
5	2.0
6	1.8
7	1.1
Average	**1.7**

Table 4.6: Cut in speed of the HAWT.

4.3 Discussion

Three important results were seen from the tests. The first is that asymmetric airfoils on a SBVAWT will allow the device to self start. Secondly, it is possible that an SBVAWT equipped with asymmetric airfoils can exhibit lower cut in speeds than a similar sized HAWT. Thirdly, SBVAWT blade orientation does play a role in cut in speed. A SBVAWT will start at lower wind speeds if its blades are in Position 2 instead of Position 1. These results are indeed encouraging for those designers and engineers interested in VAWTs. However, these tests did demonstrate some weak points though these are more associated with the researchers and not the research.

There were two prominent failures in this test. The first prominent failure was the use of an oak shaft fitted onto a metal DC motor shaft that had a course thread. An aluminum or suitable solid plastic shaft should have been used instead of wood. The second prominent failure was the lost of the anemometry data from the WindWorks digital anemometer. Luckily, the HWM 100US handheld anemometer was able to be fitted to the PVC post and data was able to be recorded.

It is important to note that the SBVAWT not only started at lower wind speed but also seemed to require a smaller amount of air than the HAWT. Attempts to start the HAWT from the same distance as the VAWT usually met with failure. Only by directing the flow of air from the carpet fan onto the blades of the HAWT would it want to start to rotate. This directing the wind did have the effect of increasing wind speed but it also increased the amount of the air blowing over the HAWT's airfoils.

CHAPTER 5

Summary

5.1 Summary

This project set out to improve the self starting abilities of SBVAWTs. Through literature review, some solutions were discovered and the research allowed some model airfoils to be built and tested. The testing demonstrated that asymmetric airfoils can enable a VAWT to self start though airfoils with a greater cord and thicker cross section work better in the lower wind speeds and Reynolds number regimes seen by VAWTs.

Asymmetric airfoils appear to also allow lower cut in speeds. This proves helpful in many locations where turbulence and lower wind speeds are common. The results of this research may be applied to developing VAWTs for operation in these lower and more turbulent wind environments.

CHAPTER 6

Future Recommendations

6.1 Research Directions

It is recommended that everyone who decides to research wind turbines either have a well equipped workshop or have access to one. Knowledge of machining is another great trait or skill to have. A balance of theoretical design and craftsmanship is an ideal blend for the work involved, especially if success is a goal.

For any future research project, the shafts of the SBVAWTs need to be rebuilt and the cut in speed tests as well as the power generation comparison with the HAWT. It is important to know how a SBVAWT truly compares with an HAWT as performance research on that topic is practically non-existent. Any VAWT needs to be supported at both the top and bottom of the blade shaft.

VAWTs can be simpler machines than HAWTs. The simplicity of design and their ability for lower wind speed operation are alluring. Even though the power produced may be small, the energy generated over the period of a year can be of great help in reducing the need for fossil fuels.

More research in airfoils is a logical place to begin. Asymmetric airfoils have not yet been wholly explored or utilized in VAWT designs. In light of the many theories concerning lift, it should be possible to fashion an asymmetric blade that incorporates elements of both Savonius and Darrieus designs and is thus able to self start and produce respectable torque as well as lift.

Ultimately, the goal is to build a wind turbine that is simple in both principle and design that can find widespread use throughout the world changing the kinetic energy of the wind into usable and environmental safe mechanical and electrical power for humanity's needs.

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